Design for Ionizing Radiation Protection

Executive Summary

During any mission, crewmembers face threats of ionizing radiation from a variety of sources. Standards outlined in NASA-STD-3001 state that individual crewmember's total career effective radiation dose during spaceflight radiation exposure is not to exceed 600 millisieverts (mSv). Additionally, short-term radiation exposure to solar particle events is limited to an effective dose of 250 mSv per event to minimize acute effects. Design choices and shielding strategies can be implemented to reduce the threat posed by radiation and ensure crew safety and health.

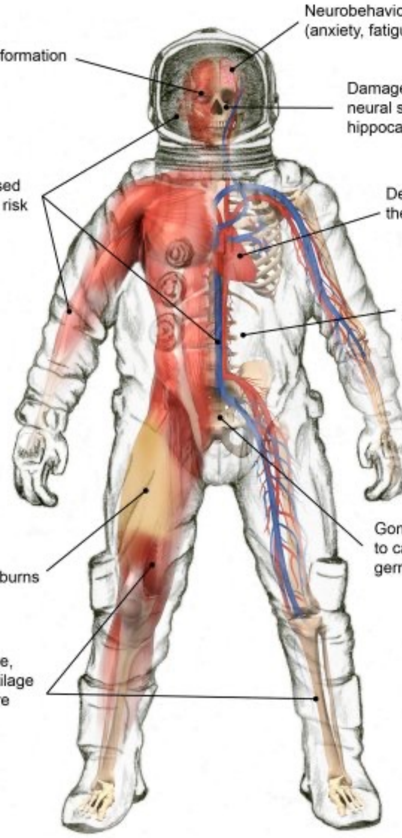
Relevant Standards

NASA-STD-3001 Volume 1, Rev B

[V1 4029] As Low as Reasonably Achievable (ALARA) Principle
[V1 4030] Career Space Permissible Exposure Limit for Space Flight Radiation
[V1 4031] Short-Term Radiation Limits – Solar Particle Events
[V1 4032] Crew Radiation Limits for Nuclear Technologies

NASA-STD-3001 Volume 2, Rev C

[V2 6095] Ionizing Radiation Protection Limit
[V2 6097] Crew Radiation Exposure Limits
[V2 6098] Radiation Environments
[V2 6099] Space Weather Monitoring
[V2 6100] Ionizing Radiation Alerting
[V2 6101] Ionizing Radiation Dose Monitoring



Select health effects due to space radiation exposures
Chancellor, J., Scott, G., & Sutton, J. (2014). Space Radiation: The Number One Risk to Astronaut Health beyond Low Earth Orbit. Life, 4(3), 491–510.

Background

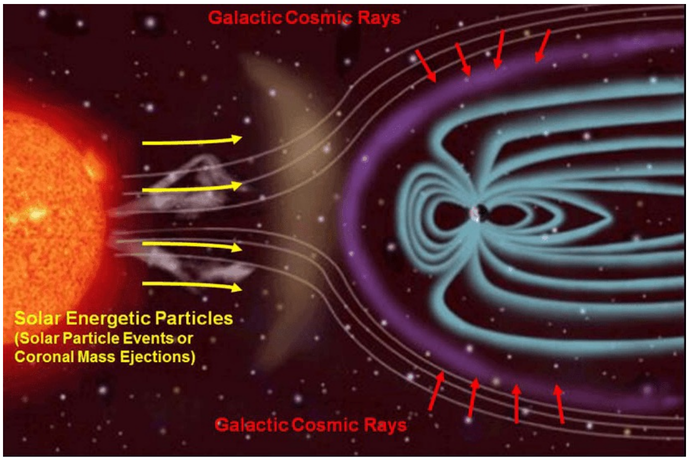
Space Radiation Environment Overview

Galactic Cosmic Rays (GCR) – penetrating protons and heavy nuclei

Occurs continuously, omni-directional, varying in flux with solar cycle. Lower GCR levels occur during solar maximum.

Shielding is **NOT** effective due to secondary radiation produced in shielding and tissue.

Countermeasures: Biological uncertainties cloud understanding of effectiveness of possible mitigations.

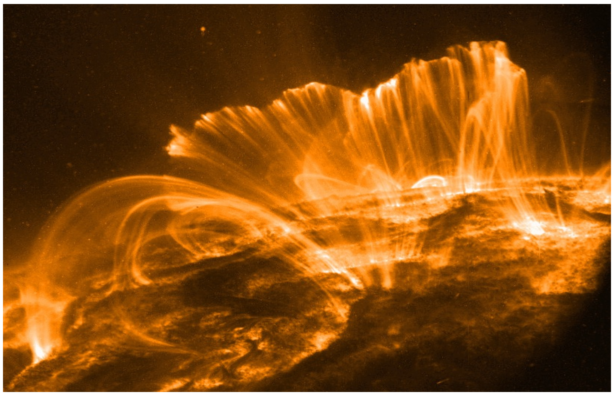


Solar Particle Events (SPE) – low to medium energy protons

Infrequent events occurring most often during solar cycle maximum (~22-year cycles) – peak activity during solar maximum.

Lunar surface provides significant protection vs. free space. Shielding (5-20 g/cm^2 aluminum and polyethylene) **IS** effective, optimization to reduce weight.

Countermeasures: Shielding, monitoring, accurate event determination, dosimetry, and timely reporting to alert crew to seek shelter are essential for crew safety.



Trapped particles are a third type of radiation that is a risk in certain circumstances (International Space Station (ISS): South Atlantic Anomaly (SAA); Lunar: Van Allen belts). These medium-to-low energy protons and electrons are a secondary source of exposure that contribute to long-term health effects (not acute). However due to short passes through the SAA and Van Allen belts, and the fact that typical SPE shielding is effective against trapped particles, additional radiation shielding is not required.

Risks of Radiation Exposure

Long Term Health Impact – Post Mission

Carcinogenesis

Radiation exposure may cause increased cancer morbidity or mortality risk for astronauts. There is also a risk of changes in cognition, motor function, and behavior or neurological disorders.

In Mission Risk

Acute Radiation Syndromes from SPEs

Acute radiation syndromes, such as nausea, vomiting, and fatigue, may occur due to in mission radiation exposure, as well as skin injuries and depletion of blood-forming organs. Effective shielding and environmental monitoring minimizes this risk. See shielding guidelines.

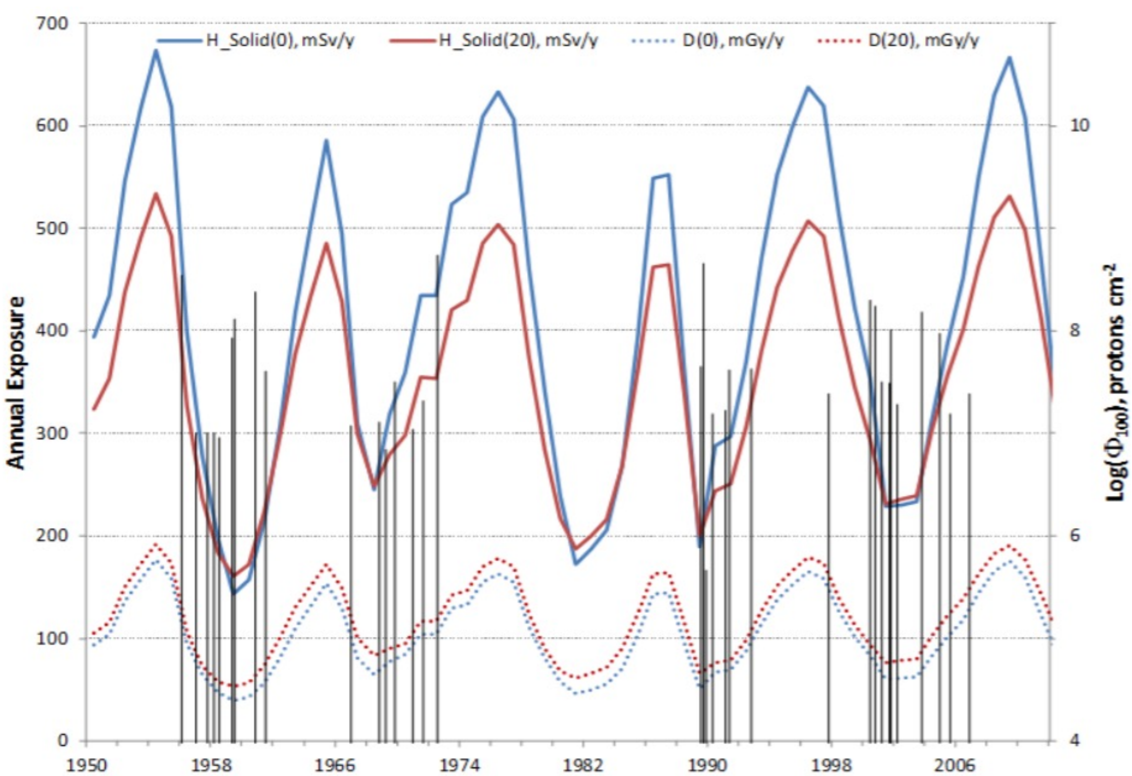
Background

Space Radiation Environment Overview

Probability of Space Radiation Events

- GCR dose & SPE probability are anti-correlated over 11-year solar cycle.
- Near or long-term prediction of SPE occurrence is not accurate, however the dose-rates for the large majority of past SPEs show real-time responses and should be adequate to reduce exposures to well below NASA dose limits.
- In an effort of prudence and preparation, current plans are in place for 1 in 100 (centennial) and 1 in 1000 (millennium) SPE events.

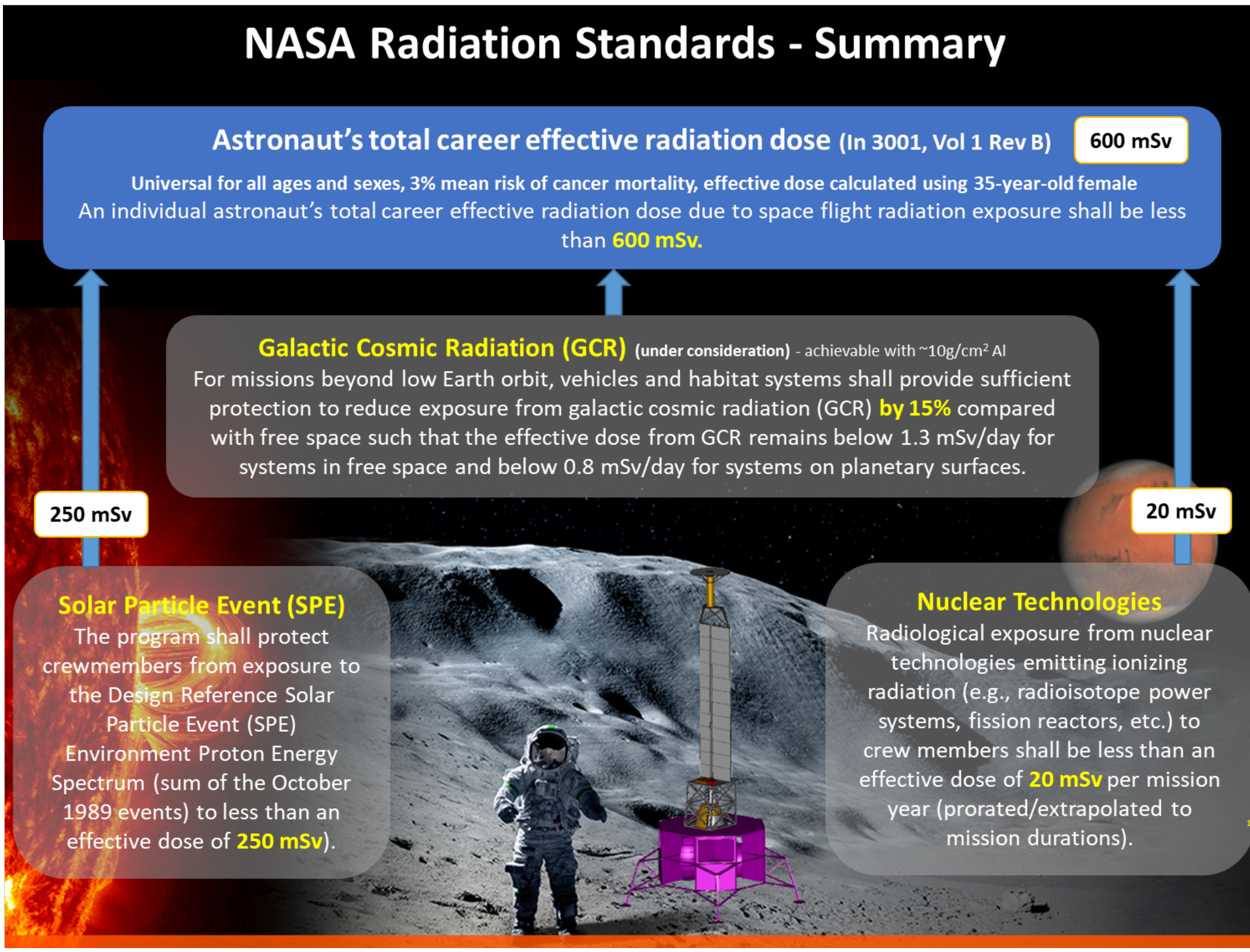
GCR Dose-Rates and SPE Occurrence



- To better understand risk of GCR exposure, dose rates are calculated utilizing simulators which retrospectively estimate secondary particle fluence as well as ambient dose equivalent rates and effective dose rates at any point in the atmosphere. Further information can be found in the reference article: *Numerical calculation of the radiation exposure from galactic cosmic rays at aviation altitudes with the Professional Aviation Dose Calculator (PANDOCA) core model* (Matthia, Meier, & Reitz, 2014).

Radiation Standards Overview

NASA updated the astronaut Space Flight Radiation Permissible Exposure Limit, the solar particle event standards and also added a nuclear technologies standard. The graphic below summarizes the standards. The standards are all based on dose (mSv) with a relationship to Risk of Exposure-Induced Death (REID) for cancer mortality. Note : The Galactic Cosmic Radiation (GCR) has not been formally adopted but is under consideration.



Career Space Permissible Exposure Limit for Space Flight Radiation [V1 4030] An individual astronaut's total career effective radiation dose due to space flight radiation exposure shall be less than 600 mSv. This limit is universal for all ages and sexes.

The NASA effective dose for determining the standard threshold limit is calculated using the NASA Q (based on the NASA cancer model of 2012), 35-year-old female model parameters (tissue weighting factors, phantom, etc.) for both males and females. Individual astronaut risk of exposure-induced death (REID) calculations are calculated using the appropriate NASA Q (based on the NASA cancer model of 2012) sex and age model parameters. See next page.

Radiation Standards Overview

The table below provides an example of a notional crewmember with three flights and their total dose exposure and mean REID calculations for both female and male.

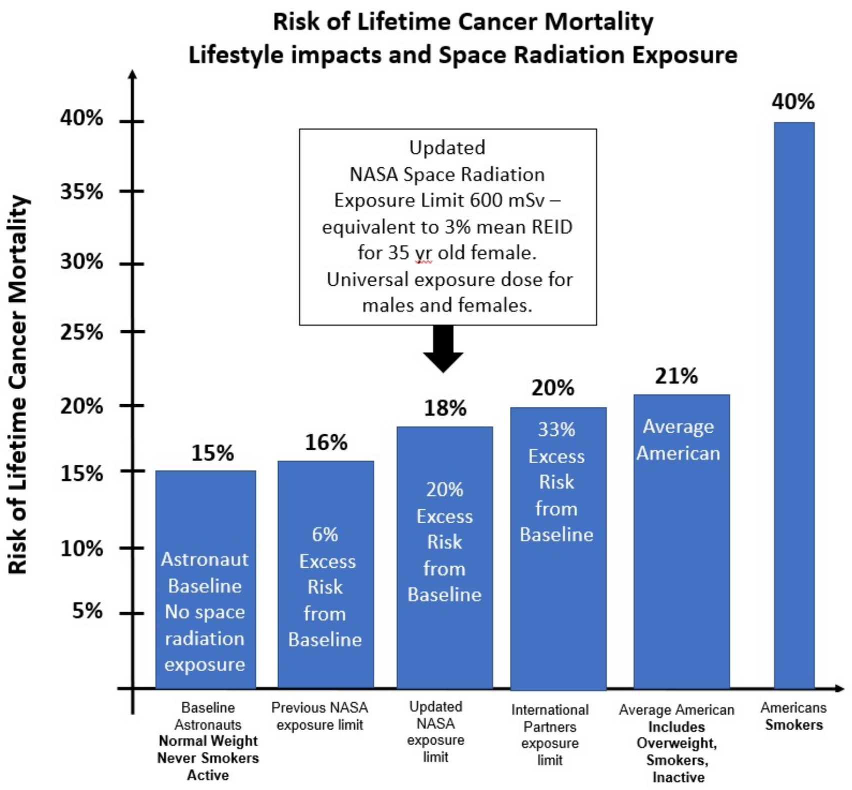
Sample Calculation – Male & Female Crewmembers - 3 Missions						
Age	**Location**	**Duration Days**	**Solar Cycle**	**Universal Effective Dose mSv**	**Female Mean REID %**	**Male Mean REID %**
38	ISS	180	Min	86	0.37	0.27
44	ISS	180	Max	77	0.31	0.23
50	Lunar Surface Mission	180	Min	167	0.62	0.45
50	Fission Power Source on Lunar Surface (Standard is < 20 mSv/year)	180	N/A	10	0.04	0.03
50	SPE Event in Orion Shielded (low probability occurrence)		N/A	125	0.50	0.37
	Totals	**540 Days**		**465 mSv**	**1.8 %**	**1.4 %**

Existing standard would limit career at ~ 1 % cumulative REID

Note: The only scenario where a crew member could be exposed to 600 mSv in one year is in deep space with a major unshielded SPE event.

465 mSv of 600 mSv Career Dose Limit

Effective dose equivalent is based on known variations in human organ susceptibility to radiation (weighting factors) to radiation of the various organs of the body and is sex dependent. To determine career dose, female weighting factors (most conservative) are utilized for both male and female crew calculations.



This graph illustrates the maximum excess risk based on the NASA spaceflight radiation exposure standard and provides a comparison to lifestyle factors.

Radiation Standards Overview

NASA-STD-3001 Volume 1 Rev B: Short-Term Radiation Limits – Solar Particle Events [V1 4031] The program **shall** protect crewmembers from exposure to the design reference solar particle event (SPE) environment proton energy spectrum (sum of the October 1989 events) to less than a NASA effective dose of 250 mSv.

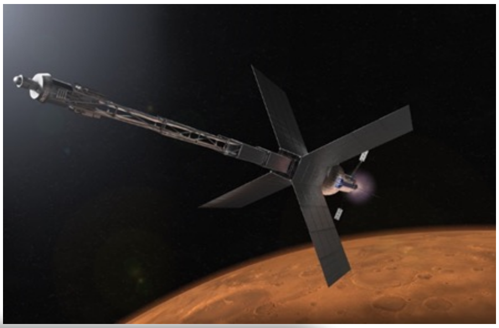
Recommendations for types of SPE shielding for mission location and duration

Mission Location and Duration	*Shielding**	*Type(s) of Shielding*	*Comments*
Celestial surface any duration	*10 cm (or g/cm^2) water equivalent surrounding the astronaut; Considers celestial surface shielding contribution*	*Reconfigurable shielding already within the vehicle*	*Timeline of SPEs allows for reconfiguration*
Beyond low earth orbit <6 months	*15 cm (or g/cm^2) water equivalent surrounding the astronaut*	*Reconfigurable shielding already within the vehicle; Shielding may include personal protective equipment (PPE)*	*Timeline of SPEs allows for reconfiguration*
Beyond low earth orbit > 6 Months	*20 cm (or g/cm^2) water equivalent surrounding the astronaut*	*Integrated vehicle and/or reconfigurable Shielding which may include PPE*	*Long duration missions increase the probability of the crew being exposed SPEs*

**The shielding required to meet the standard (utilizing existing mass when feasible).*

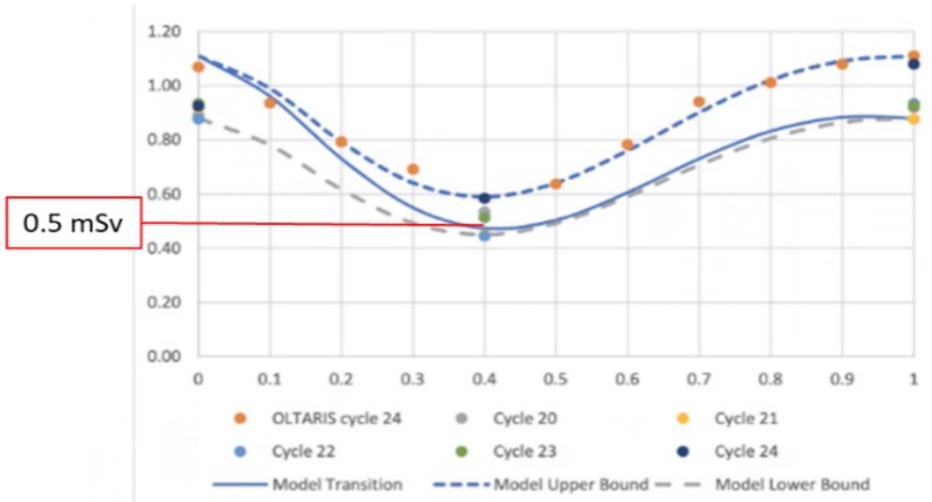
NASA-STD-3001 Volume 1 Rev B: Crew Radiation Limits for Nuclear Technologies [V1 4032] Radiological exposure from nuclear technologies emitting ionizing radiation to crewmembers (e.g., radioisotope power systems, fission reactors, etc.) shall be less than an effective dose of 20 mSv per mission year (prorated/extrapolated to mission durations).

This limit is based on not adding more than 10% radiation exposure beyond the space environment radiation of the mission. Based on an analysis for a surface-based mission, the radiation environment exposure is approximately 0.5 mSv per day; and 10% of this value sets the standard to 0.05 mSv per day and ~20 mSv/mission year. This standard is applied to both surface and free-space missions regardless of mission solar cycle. Exact mission assumptions should be considered when performing the calculation; parameters should include estimates of time in a habitat, habitat shielding, and EVA frequency. For missions that are leveraging nuclear sources for a propulsion system, the tradeoff of reduced mission duration due to faster transit which reduces the crew exposure to space flight radiation exposure should be considered compared to the increased exposure due to the nuclear source. For example, if the nuclear propulsion system saved 90 days of exposure during the transit to Mars which equates to 1.5 mSv/day × 90 days = 135 mSv “saved” space flight radiation exposure and the source generates 150 mSv, then the net exposure is +15 mSv.



Reference Data

Effective Dose (mSv per Mission Day) Variation with Solar Cycle

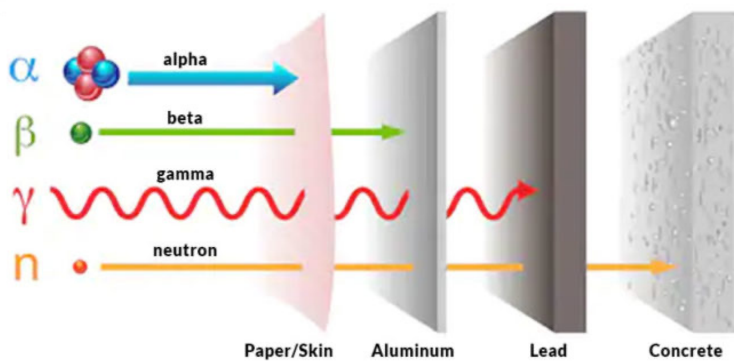


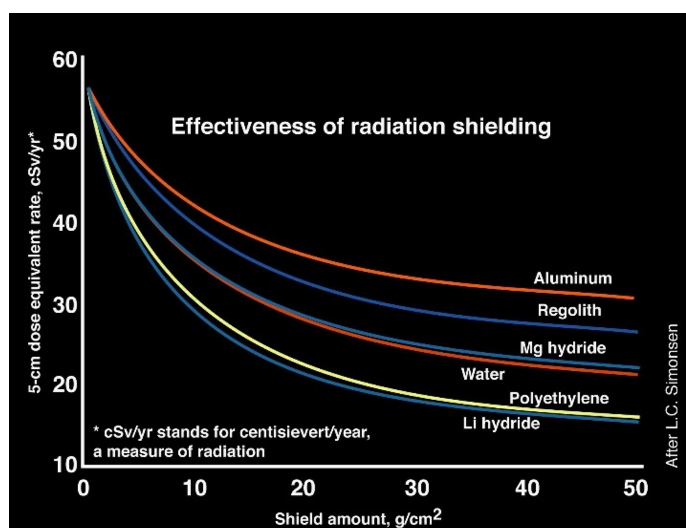
Engineering Countermeasures

- The best way to shield from ionizing radiation is to provide as much physical material between a person and the source of radiation as possible. Dense and thick materials that essentially absorb the high energy particles from incoming radiation are ideal but prove difficult in space travel due to their significant amounts of mass.

Shielding Materials

- Aluminum and polyethylene are the most commonly used shielding materials. They provide an average 50% reduction in dosage levels from SPE radiation. GCR radiation does not respond to shielding, with only an average 7% reduction in dosage levels. Additionally, secondary radiation is produced within tissues, further reducing any benefits of GCR shielding.

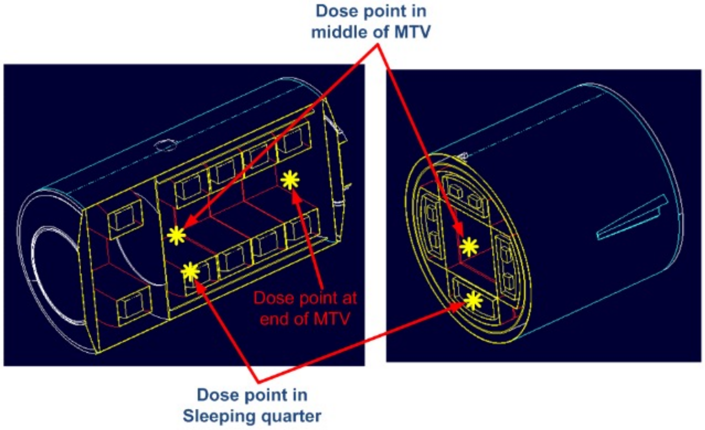




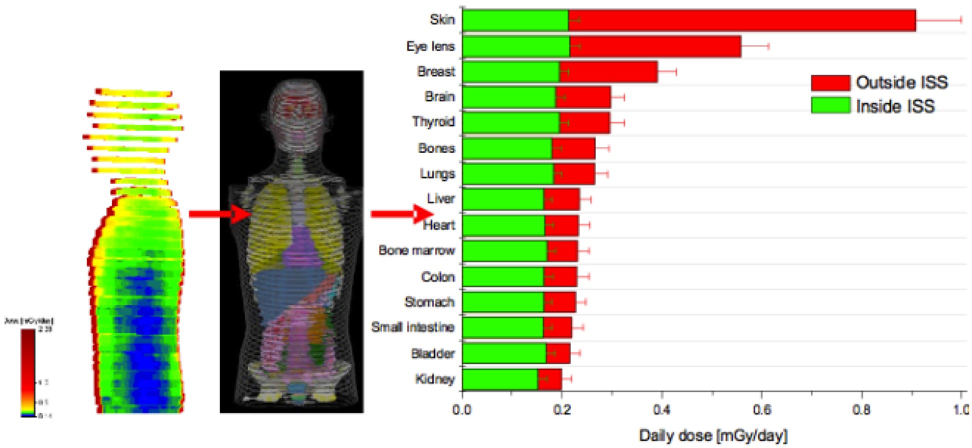
Reference Data

Ray Tracing tools and Effectiveness of Shielding

Ray Tracing technology examines the effectiveness of shielding tools in blocking radiation. Evenly distributed rays are created to start from dose point and end outside the vehicle. Each ray records distance and respective density of the parts it passes. Areal mass density is calculated and used in transport code that evaluates particle flux at dose point.



Effect of ISS Shielding on crew daily dose



Effect of using water bags/stowage as a shelter during an SPE event beyond low earth orbit in a Capsule

Effective Dose (mSv) by crew location within capsule*	Crew #1	Crew #2	Crew #3	Crew #4
Effective Dose E	214	210	259	231
Effective Dose (Optimized Pre-Launch Stowage)	68	65	66	66
Effective Dose (Optimized Return Stowage)	83	75	73	83

*Note the different doses based on location within a vehicle

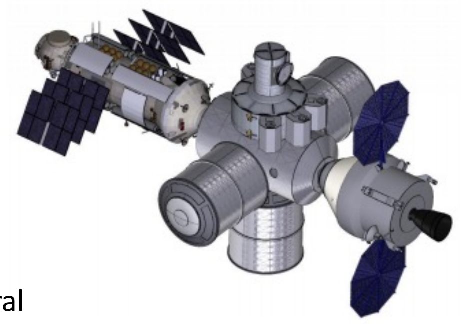
Application Notes

Design Considerations

- Shielding design must implement ALARA for mission duration < 6 months with respect to SPE protection.
- For missions > 6 months, it is recommended that vehicle shielding be at least 20 g/cm^2 to protect the crew from SPEs.
- Storm shelter: Additional Storm Shelter with an added 10 cm water equivalent in crew quarters to protect against centennial solar particle event.
  - This can be achieved by rearranging items such as water containers and/or high hydrogen content materials.
  - Timelines of SPEs allow sufficient time for re-configuration.
  - Protection for a 1000-year SPE event would require ~20 cm water equivalent for shielding.
- Due to the nature of GCRs, shielding is less effective. GCR particles scatter into multiple particles when they strike shielding.
- Radiation alerting provides an additional layer of protection to limit exposure to SPEs (early warning allows for crew to safe vehicle and configure shelter).
  - Real-time alert dosimetry also provides a very high level of protection for EVAs if termination occurs within 2 hours and there is access to shielding.
- Radiation dose monitoring provides critical occupational health information to understand the effects of radiation exposure.
- Designs can be evaluated and maximized for shielding effectiveness utilizing existing Shield Geometry Model and Shielding Analysis by computer-aided design (CAD) tools, as well as conducting Ray Tracing.

Vehicle Design Considerations

- Current engineering and design teams are researching the possibility of utilizing a 'surrounded' vs. 'in-line' architecture approach for crew habitat in hopes that there is a reduction in overall exposure to GCR radiation. A surrounded architecture approach utilizes the hub and spoke ideology, with a centralized node module acting as the core/hub at the center of the layout where crew activity takes place most of the time. The structure surrounding the core/hub would be comprised of major structural elements that contain logistics, equipment, trash, props, etc.



Source: Bailey (2012) – Deep Space Habitat Project

Application Notes

Guidelines for Space Radiation Shielding Requirements for Exploration Missions

- NASA's Health and Medical Technical Authority has developed Shielding Requirement Guidelines for exploration missions that were reviewed by Space Radiation Research Clinical Advisory Panel (RCAP). These Guidelines are intended to provide closure for vehicle design requirements.
  - Analysis shows decennially large SPEs lead to doses for average spacecraft shielding below NASA Dose limits requiring only ALARA.
  - However centennial and millennial events require a well designed "storm shelter".
- Large majority (~95%) of SPEs require only ALARA considerations and do not approach dose limits.
  - A Centennial Event (1 per 100 years) can be shielded below NASA dose limits with additional 10 cm water equivalent storm-shelter shielding.
  - Millennial Event (1 per 1000 year) with additional 20 cm water equivalent storm-shelter shielding.
- Assuming a vehicle with 20 g/cm^2 aluminum – Additional Storm Shelter with additional 10 cm water equivalent in crew quarters to protect against centennial solar particle event.
  - Combination of inherent and reconfigurable shielding.
  - Timelines of SPEs allow sufficient time for re-configuration.
- Mission disruption is a major risk from SPEs, especially for extravehicular activities (EVAs).
  - Spacecraft shielding requirements could be impacted by additional doses incurred by crew during EVA, especially on lunar surface.
  - Real-time alert dosimetry provides a very high level of protection if EVA termination occurs within 2 hrs.
  - The probability of EVA organs doses >100 mSv is less than one in a million based on SPE statistics of event frequency, size and energy spectra.
- Shielding guidelines could be modified by new knowledge of GCR, central nervous system functioning, cancer, and other risks.

Back-Up

Major Changes Between Revisions

Rev C → Rev D
- Updated information to be consistent with NASA-STD-3001 Volume 1 Rev B and Volume 2 Rev C.

Rev B → Rev C
- Added information regarding shielding materials and vehicle/spacecraft design considerations.
- Added information regarding frequency of radiation events.
- Added additional information about ray tracing.
- Added new HMTA proposed guidelines for space radiation shielding requirements.
- Overall formatting/template updates.

Referenced Standards

NASA-STD-3001 Volume 1 Revision B

[V1 4029] As Low as Reasonably Achievable (ALARA) Principle All crew radiation exposures shall be minimized using the ALARA principle.

[V1 4030] Career Space Permissible Exposure Limit for Space Flight Radiation An individual astronaut's total career effective radiation dose due to space flight radiation exposure shall be less than 600 mSv. This limit is universal for all ages and sexes.

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[V1 4032] Crew Radiation Limits for Nuclear Technologies Radiological exposure from nuclear technologies emitting ionizing radiation to crewmembers (e.g., radioisotope power systems, fission reactors, etc.) shall be less than an effective dose of 20 mSv per mission year (prorated/extrapolated to mission durations) and utilizing the ALARA principle.

NASA-STD-3001 Volume 2 Revision C

[V2 6095] Ionizing Radiation Protection Limit The program shall set system design requirements to prevent potential crewmembers from exceeding PELs as set forth in NASA-STD-3001, Volume 1.

[V2 6097] Crew Radiation Exposure Limits The program/project shall design systems using the ALARA principle to limit crew radiation exposure.

[V2 6098] Radiation Environments The program shall specify the radiation environments to be used in verifying the radiation design requirements.

[V2 6099] Space Weather Monitoring The program shall set requirements specifying appropriate capabilities to be provided for real-time monitoring of space weather (solar particle events (SPE), galactic cosmic rays (GCR), etc.) for characterization of the radiation environment and operational response by ground personnel and the crew.

[V2 6100] Ionizing Radiation Alerting The system shall include a method to alert all crewmembers the crew locally and remotely when radiation levels are expected to exceed acceptable levels.

[V2 6101] Ionizing Radiation Dose Monitoring To characterize and manage radiation exposures, the program shall provide methods for monitoring personal dose and dose equivalent exposure, ambient monitoring of particle fluence as a function of direction, energy, and elemental charge and monitoring of ambient dose and ambient dose equivalent.

References

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